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Atrial myocardial deformation properties are temporarily reduced after cardioversion for atrial fibrillation and correlate well with left atrial appendage function

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Aim This study was conducted to evaluate whether left atrial strain and strain rate correlate well with transesophageal parameters of stunning after atrial fibrillation.
Methods and results Twenty-two consecutive patients with chronic atrial fibrillation $\geq$3 months and $<$1 year were enrolled in the study. Transthoracic (TTE) and transesophageal (TEE) echocardiography with color Doppler myocardial imaging were performed before, 1 day after and 10 days after successful cardioversion. Left atrial transthoracic strain (S) and strain rate (SR) from lateral, inferior and anterior atrial walls, left atrial appendage tissue velocities, strain and strain rate values were measured with offline analysis. Left atrial appendage emptying (LAAEV) and filling (LAAFV) velocities were obtained from transesophageal echocardiography.

Left atrial transthoracic, and left atrial appendage strain and strain rates were significantly lower following 1 day after cardioversion (TTE S/SR, $5.0 \pm 2.8\%/2.3 \pm 1.0$; TEE (septal) S/SR, $7.6 \pm 3.6\%/1.6 \pm 0.7$). There was a good correlation between these parameters and LAAEV (LA systolic strain and LAAEV, $r = 0.73$, $P = 0.007$). Left atrial and LAA strain and strain rate values improved over time, and correlated well with LAAEV, measured 10 days after cardioversion.
Conclusions Transthoracic atrial and TEE LAA strain and strain rate, which are quantitative measures of atrial function, are reduced after cardioversion, and recover subsequently. The good correlation between LAA function and TTE strain and strain rate suggests that TTE atrial parameters may help determine duration of anticoagulation.

Introduction

Atrial fibrillation (AF) is the most frequently seen sustained arrhythmia in clinical practice, and is closely associated with an increased cardiovascular morbidity and mortality.[1] The loss of atrial activity leads to insufficient atrial emptying and impaired ventricular function. Electrical and structural remodelling starts shortly after the onset of AF.[2] Electrical or pharmacological cardioversion is the most effective treatment modality in restoring sinus rhythm in patients with AF. However, a transient decrease in atrial mechanical function, termed atrial stunning, is a well documented condition after cardioversion of AF.[3] Despite reversion to sinus rhythm, atrial stunning leads to reduction in atrial and appendage blood flow velocities, thus it is responsible for an increase in the risk of thromboembolic complications.[4]

New echocardiographic techniques such as color Doppler myocardial imaging derived strain and strain rate parameters have made it feasible to look at atrial myocardial deformation properties, and SR/S imaging for the quantification of longitudinal myocardial LA deformation has been validated as a technique.[5] Atrial strain and SR have been documented to be altered in AF and can be used as predictors of maintenance of the sinus rhythm.[6] However, there is little information related to atrial and atrial appendage myocardial deformation velocities in AF. The quantification

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of atrial dysfunction may also identify the patients for whom anticoagulation is obligatory for a longer time.

We aimed to evaluate the feasibility of measuring left atrial mechanical stunning after cardioversion with TTE and TEE left atrial appendage color Doppler imaging derived strain and strain rate parameters.

Methods

Study population

We included 22 consecutive patients (8 men; mean age 64) with chronic atrial fibrillation ($\geq$3 months, $<$1 year in duration) in the study. Patients with valvular diseases, prosthetic valves, pericarditis, acute myocardial infarction, chronic lung disease, recent heart surgery, hyperthyroidism, pacemaker implantation and presence of atrial thrombus by TEE were excluded from the study.

Drug treatment of patients before cardioversion included beta blockers (55%), digoxin (38%), and calcium channel blockers (33%). All patients were taking anticoagulant therapy.

Transthoracic and transesophageal echocardiography were performed before cardioversion, 1 day and 10 days after cardioversion in all patients. Electrical cardioversion (CV) was performed with direct-current shock using anterior-lateral paddles in fasting patients with short term intravenous sedation. A mean 200 J of electrical energy was delivered to all patients, starting from 150 J up to maximum of 360 J. None of the patients were intubated. Successful cardioversion was defined as a stable sinus rhythm at least 1 day after cardioversion. All patients cardioverted to sinus rhythm successfully. The study was approved by the local ethics committee for human research, and all patients gave written informed consent to the study.

Echocardiography

All patients were evaluated by a complete transthoracic echocardiography with a 2.5-MHz transducer attached to a commercially available echocardiographic machine (Vingmed System Five, General Electric Medical Systems, Horten, Norway). Images were acquired with patients at rest, lying in left lateral and supine position. Routine echocardiographic measurements were performed from parasternal short and long-axes, and apical 4- and 2-chamber views. Interventricular septal and left ventricular (LV) posterior wall thicknesses and LV dimensions were measured by M-mode from parasternal long-axis window. LV ejection fraction was calculated. Left atrial (LA) dimensions were measured in the anteroposterior from parasternal long-axis view.

Transthoracic color Doppler myocardial images were acquired at a frame rate of 200 s^{-1} by using a narrow image sector angle (30°) at the end of expiration. The region of interest was positioned at the center of the ultrasound sector to keep the direction of the ultrasonographic beam as parallel as possible to the long-axis motion. All images were stored digitally and analyzed offline by using software (Echopac, GE Vingmed). Strain and strain rate values were obtained from mid segment of left atrial lateral (apical 4-chamber), anterior and inferior (apical 2-chamber) walls (*Figure 1*). Longitudinal motion of atria was described as rate of lengthening in systole (positive strain rate) and rate of shortening in diastole (negative strain rate). Electrocardiographic R peak was used to define end-diastole and the end of the electrocardiographic T wave was used to define end-systole. Peak positive systolic and early diastolic values were calculated from offline analysis. All values were calculated over five cardiac cycles and then averaged to get mean strain and strain rate from three walls (respectively lateral, inferior and anterior left atrial walls).

Transesophageal echocardiography was performed by using a 5-MHz multiplane transducer. Patients were examined in the fasting state, after the application of topical pharyngeal anesthesia.

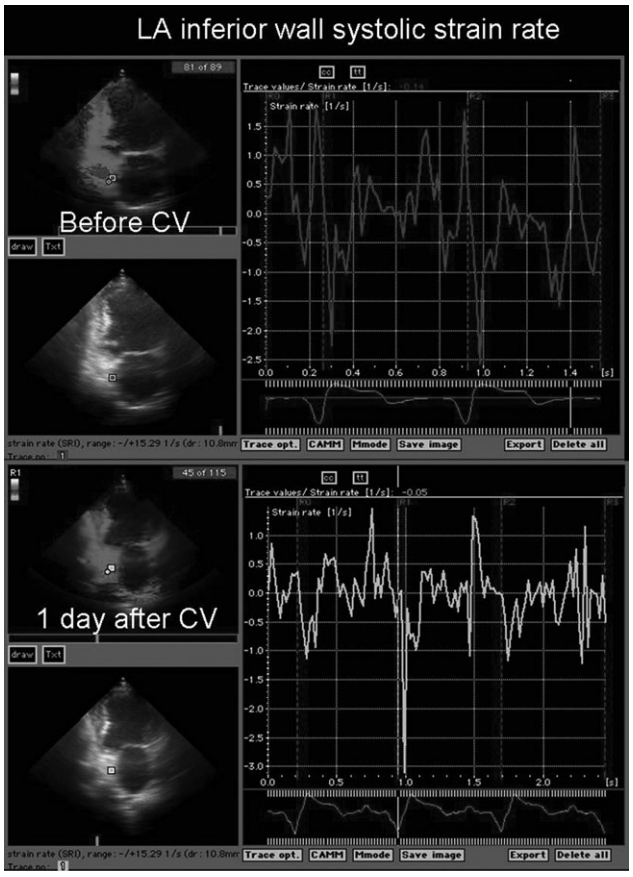

Figure 1 Inferior wall strain rate from apical 2-chamber view, before cardioversion and 1 day after cardioversion.

Left atrial appendage (LAA) was clearly visualized in the mid-esophageal view by a stepwise rotation of the imaging sector of 0° to 150°. Left atrial peak emptying (LAAEV) and filling velocities (LAAFV) were measured by placing pulsed wave Doppler sample volume into the orifice of LAA in the longitudinal view (imaging sector angle 45° to 75°). An optimal parallel angle between insonating beam and flow was maintained. LAAEV was defined as a late diastolic positive, and LAAFV defined as early systolic negative Doppler outflow signal. These two values were averaged from at least five consecutive cardiac cycles. In the same view, a pulsed wave tissue Doppler sample volume was placed within the proximal third of the septal (TDI-s) and in the midlateral (TDI-l) walls of the LAA. We used triphasic (sinus rhythm) and biphasic (AF patients) flow patterns described by Parvathaneni and colleagues.[7] D1 was calculated from the first upward velocity during early in diastole (before P wave) in patients with sinus rhythm. D2 (upward emptying) and D3 (downward filling) velocities were measured (after P wave). Patients with AF showed multiphasic irregular fibrillatory emptying and filling velocities. An average of 10 D2 and D3 values were calculated in patients with AF. Color Doppler images were acquired from the same view. Strain and strain rate values were obtained from mid portion of the septal and lateral walls of LAA (*Figure 2*).

Statistical analysis

Data are expressed as mean $\pm$ standard deviation (SD) if values were distributed normally, as median (minimal vs. maximal) if not. Differences within patient changes were tested by repeated measures analysis of variance (ANOVA). To test reproducibility within and between observers, 8 randomly chosen patients'

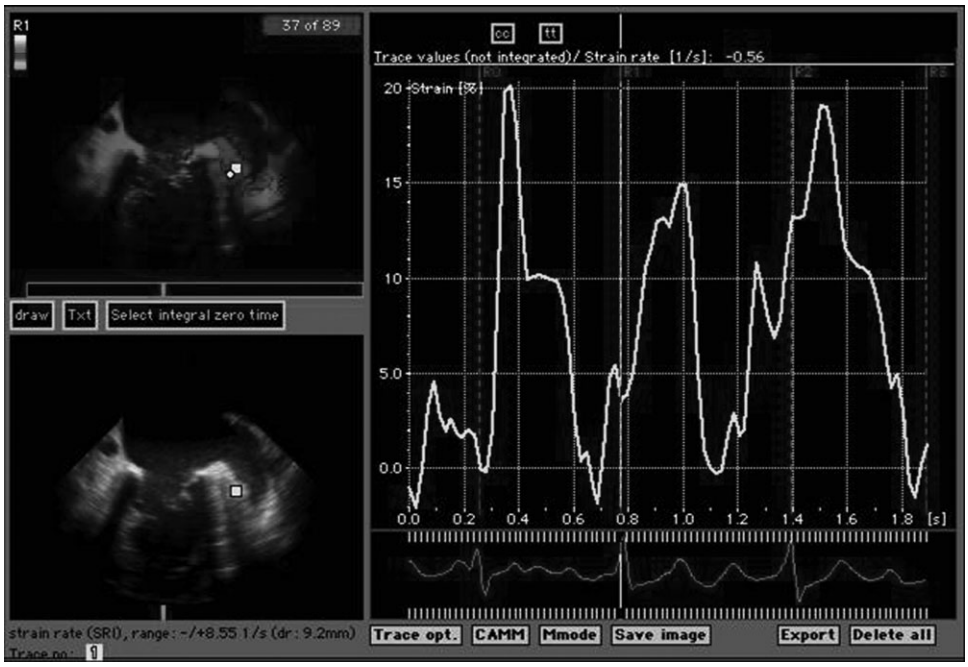

Figure 2 Left atrial appendage septal wall strain from mid-esophageal view.

values were analyzed by Blande–Altman methods. Spearman rank correlation test was used to compare the associations between parameters. A *p* value of 0.05 or less was considered significant. All analyses were calculated with SPSS version 11.0 for Windows (SPSS Inc., Chicago, IL).

Results

The baseline clinical and echocardiographic characteristics of the studied samples are presented in *Table 1*. Left ventricular diastolic and systolic dimensions and left ventricular ejection fraction were within normal values in all patients (LVEF $59.6 \pm 4.5\%$), but the left atrium dimension was slightly enlarged (44.1 ± 2.3 mm).

Transthoracic color Doppler myocardial imaging

Mean systolic and early diastolic myocardial strain and strain rate values were significantly lower 1 day after cardioversion compared to basal measurements (*Table 2*). Mean left atrial systolic strain increased from $5.0 \pm 2.8\%$ (1 day after CV) to $10.7 \pm 4.5\%$ (10 days after CV, $P < 0.001$) (*Figure 3*). Mean left atrial systolic strain rate was also significantly improved 10 days after CV, when compared with 1 day after CV (2.3 ± 1.0 vs. 2.7 ± 1.1, $p < 0.001$).

Transesophageal echocardiography

Transesophageal echocardiography was successfully performed in all patients without premature interruption, and no complications were noted during and after examination. Left atrial appendage emptying and filling velocities were decreased following CV (LAAEV 48.68 ± 12.6 vs. 30.73 ± 5.6 cm s^{-1}, $P = 0.005$; LAAFV 54.72 ± 17.4 vs. 48.97 ± 11.4, $P < 0.001$). LAAEV was significantly greater 10 days after CV (59.37 ± 15.3 cm s^{-1}). The peak LAA tissue Doppler mid-septal and mid-lateral D2 and D3 flow velocities were reduced after cardioversion (*Table 3*). When compared with basal values, LAA tissue Doppler septal and lateral velocities were significantly increased 10

Table 1 Baseline characteristics of the patients

Total	22
Age (years)	63.9 ± 5.1
Men	8
Duration of AF	$\geq$3 months $<$1 year
LA size (mm)	44.1 ± 2.3
LVEDD (mm)	51.4 ± 5.1
LVESD (mm)	35.41 ± 4.5
LVEF (%)	59.6 ± 4.5

LA, left atrium; LVEDD, left ventricular end-diastolic diameter; LVESD, left ventricular end-systolic diameter; LVEF, left ventricular ejection fraction.

Table 2 Mean systolic and diastolic myocardial strain and strain rates before, 1 day after and 10 days after cardioversion

	Pre-CV	1 day after CV	10 days after CV
Mean LA systolic strain (%)	12.14 ± 4.8	5.0 ± 2.8*	$10.7 \pm 4.5^{\dagger}$
Mean LA diastolic strain (%)	8.4 ± 3.8	6.8 ± 3.2*	$7.6 \pm 3.8^{\dagger}$
Mean LA systolic strain rate (s^{-1})	3.2 ± 1.5	2.3 ± 1.0*	$2.7 \pm 1.1^{\dagger}$
Mean LA diastolic strain rate (s^{-1})	-2.6 ± 0.7	-1.8 ± 0.7*	$-2.6 \pm 1.0^{\dagger}$

CV, cardioversion; LA, left atrium. *$P < 0.05$, Pre-CV vs. 1 day after CV; $^{\dagger}P < 0.05$, 1 day after CV vs. 10 days after CV.

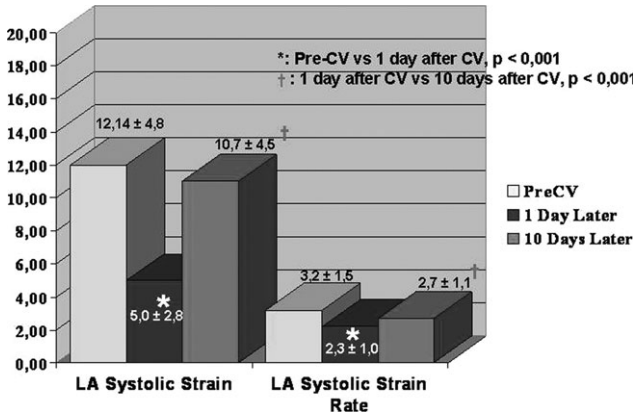

Figure 3 Comparison of LA systolic strain and strain rate values, before, 1 day and 10 days after CV.

Table 3 Comparison of left atrial appendage tissue Doppler velocities before, 1 day after and 10 days after cardioversion

	Pre-CV	1 day after CV	10 days after CV
Peak LAA septal D2 (cm s^{-1})	7.1 ± 1.7	5.5 ± 1.3*	$10.01 \pm 2.7^{\dagger}$
Peak LAA septal D3 (cm s^{-1})	-8.8 ± 2.5	-7.3 ± 2.4*	$-11.7 \pm 2.8^{\dagger}$
Peak LAA lateral D2 (cm s^{-1})	8.6 ± 3.1	7.6 ± 2.3	$12.00 \pm 4.5^{\dagger}$
Peak LAA lateral D3 (cm s^{-1})	-8.4 ± 2.2	-7.1 ± 1.6*	$-12.23 \pm 3.2^{\dagger}$

CV, cardioversion; LAA, left atrial appendage. *$P < 0.05$, Pre-CV vs. 1 day after CV; $^{\dagger}P < 0.05$, 1 day after CV vs. 10 days after CV.

days after cardioversion. The differences of left atrial appendage systolic and diastolic strain and strain rate measurements from side walls (septal and lateral) within patients' changes between days are given in *Table 4*.

Left atrial appendage lateral wall systolic strain decreased from $10.4 \pm 5.6\%$ to $7.8 \pm 4.8\%$ 1 day after cardioversion. Similarly LAA lateral wall strain rate was significantly compromised after cardioversion. However, 10 days after cardioversion LAA systolic strain and strain rate values were improved.

Comparing LA appendage emptying velocity with transthoracic left atrial and transesophageal LAA color Doppler imaging indexes, we found a significant correlation between mean LA systolic strain and LAAEV ($r = 0.73$, $P = 0.007$). Mean LA systolic strain rate also correlated to LAAEV ($r = 0.71$, $P < 0.05$). Left atrial systolic strain and strain rate values correlated well to LAA systolic septal strain and strain rate values ($r = 0.78$, $P < 0.01$; $r = 0.83$, $P = 0.001$).

Eight patients were randomly selected for interobserver and intraobserver variability test by Blande–Altman analysis. Left atrial systolic and diastolic strain, LA systolic and diastolic strain rate, LAA systolic and diastolic strain, and LAA systolic and diastolic strain rate were remeasured by the same observer and by another independent observer. There were no systematic differences between measurements (*Table 5*).

Table 4 The comparison of left atrial appendage systolic and diastolic strain and strain rate values from side walls before, 1 day after and 10 days after cardioversion

	Pre-CV	1 day after CV	10 days after CV
LAA systolic strain lateral (%)	10.4 ± 5.6	7.8 ± 4.8*	$15.7 \pm 5.4^{\dagger}$
LAA systolic strain septal (%)	8.9 ± 3.5	7.6 ± 3.6*	$15.19 \pm 4.8^{\dagger}$
LAA systolic strain rate lateral (s^{-1})	2.1 ± 0.8	1.9 ± 0.9	$3.7 \pm 1.2^{\dagger}$
LAA systolic strain rate septal (s^{-1})	2.27 ± 0.5	1.6 ± 0.7*	$4.2 \pm 0.9^{\dagger}$
LAA diastolic strain lateral (%)	-6.8 ± 3.1	-5.1 ± 2.9*	$-8.5 \pm 3.7^{\dagger}$
LAA diastolic strain septal (%)	-6.5 ± 2.1	-4.7 ± 1.8*	$-7.2 \pm 2.2^{\dagger}$
LAA diastolic strain rate lateral (s^{-1})	-2.56 ± 1.1	-1.3 ± 1.0*	$-3.9 \pm 1.1^{\dagger}$
LAA diastolic strain rate septal (s^{-1})	-2.4 ± 0.9	-1.7 ± 0.6*	$-4.3 \pm 1.1^{\dagger}$

CV, cardioversion; LAA, left atrial appendage. *$P < 0.05$, Pre-CV vs. 1 day after CV; $^{\dagger}P < 0.05$, 1 day after CV vs. 10 days after CV.

Discussion

This study showed that left atrial myocardial deformation properties obtained from either TTE or TEE color Doppler imaging were significantly compromised in patients with atrial fibrillation, 1 day after successful cardioversion. However, these parameters recovered significantly 10 days after electrical cardioversion. This improvement of the new echocardiographic parameters was in parallel to the LAA flow velocity changes.

Cardioversion of AF to sinus rhythm is an effective way of treatment, but the transient mechanical dysfunction of atria is one of the major concerns because of an increased risk of postcardioversion thromboembolism.[8] Several echocardiographic parameters, such as decreased left atrial appendage flow velocities, decreased left atrial appendage emptying fraction, decreased transmitral inflow velocity and appearance of spontaneous echo contrast have been used to assess the atrial stunning.[9–11] Most of the studies on atrial stunning evaluated the left atrial appendage velocities.[12,13] These studies showed that LAA flow is one of the strongest predictors of atrial dysfunction and sinus rhythm maintenance.[14]

The longitudinal lengthening and shortening of the atrium during systole and diastole can be distinguished by atrial strain rate measurements, since these parameters demonstrate a site specific directional difference. Thus, atrial strain and strain rate can give more quantitative information about atrial myocardial function. Di Salvo and coworkers[15] demonstrated that atrial deformation properties such as atrial lengthening and shortening were significantly reduced during recent-onset lone atrial fibrillation by using color Doppler myocardial imaging. They also reported no atrial deformation during late diastole. These findings confirm that the conduit and reservoir function of atrium are compromised and atrial pumping function is absent during AF. The dysfunction

Table 5 Inter- and Intra-observer variability test results

Parameters	Inter-observer variability		Intra-observer variability	
	Mean difference	%	Mean difference	%
Lateral LA systolic strain (%)	1.1	9.2	0.9	7.4
Lateral LA diastolic strain (%)	−1.0	11.7	1.1	12.1
Lateral LA systolic strain rate (s^{-1})	−0.5	12.1	0.4	11.6
Lateral LA diastolic strain rate (s^{-1})	0.4	11.1	0.2	6.6
LAA systolic strain lateral (%)	1.2	10.9	−0.7	6.4
LAA systolic strain septal (%)	−0.9	9.5	−0.5	5.5
LAA systolic strain rate lateral (s^{-1})	−0.3	10.5	0.2	8.6
LAA systolic strain rate septal (s^{-1})	0.4	11.4	−0.1	4.3
LAA diastolic strain lateral (%)	0.8	11.2	0.6	8.5
LAA diastolic strain septal (%)	1.0	12.3	−0.4	5.7
LAA diastolic strain rate lateral (s^{-1})	−0.3	8.7	−0.2	7.6
LAA diastolic strain rate septal (s^{-1})	0.5	10.1	0.3	10.1

LA, left atrium; LAA, left atrial appendage.

and stunning of atrium following cardioversion has been evaluated by several invasive and noninvasive techniques. However, the sensitivity of strain and strain rate imaging in detecting myocardial dysfunction is superior due to its independence from global cardiac motion and the tethering effect. Atrial strain rate was found to be reduced in patients with chronic atrial fibrillation following cardioversion to sinus rhythm.[16]

During AF, there is a structural and electrophysiological atrial remodeling, which leads to an increased atrial stiffness.[17] Tachycardia-induced atrial cardiomyopathy, atrial hibernation with myolysis, dedifferentiation of myocytes to the fetal life, and atrial fibrosis have been suggested to be responsible for atrial dysfunction and stunning.[3] Our findings show that new echocardiographic indexes may detect atrial myocardial abnormalities, which are observed during AF and early after cardioversion. During ventricular systole, the atria act as a reservoir for blood filling from pulmonary veins. During this phase strain profile shows lengthening, which is affected mainly by atrial relaxation and stiffness.[15] In our study, the reduced LA and LAA systolic strain and strain rate point out the abnormal atrial reservoir function implicating impaired atrial myocardial compliance. During ventricular diastole the atrium functions as a conduit, passively emptying the blood and contracting, permitting the emptying of more blood into the left ventricle. The decreased LA/LAA diastolic strain and strain rate values early after cardioversion demonstrate impaired left atrial functions during ventricular diastole, showing atrial stunning.

The significant correlation between LA and LAA systolic strain/strain rate and left atrial appendage emptying velocity implies that new myocardial deformation indexes, which are derived from echocardiography, can detect atrial dysfunction and stunning early after cardioversion in patients with atrial fibrillation. Although systolic LA and LAA S/SR are concerned with the reservoir function of the atrium, all functions of the atrium (reservoir, conduit, and contractile) are decreased during atrial stunning. Since there is no contractile function during AF, systolic S/SR can be used to show stunning due to AF and is correlated with LAAEV, which is the most reliable parameter showing atrial stunning.

Since TEE is a semi-invasive technique, it cannot be repeated frequently after CV. Our findings showing that LA S/SR correlate well and move in parallel to LAA contraction and LAA strain imply that serial TTE can be used to follow patients with stunning. This may have important implications for the duration of anticoagulation.

Conflict of interest: none declared.

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